Monitoring DC stray current interference of steel sheet pile structures in railway environment

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Steel structures near DC powered railways are expected to be affected by stray current interference. This causes accelerated corrosion rates. Therefore steel is often not used as a building material in these cases, although certain advantages over the alternative material concrete exist. These advantages can include amongst others costs, shorter building time and less nuisance during construction.

In this paper a non-destructive DC stray current monitoring system is described and the measurement results from a large-scale field test are given. The monitoring system consisted of specially developed coupon sensors for sheet pile walls with which stray currents could be measured, and so-called Reference Electrode (RE's), with which electrical potentials were measured. An advanced cost-effective monitoring system was developed, using a zero resistance current measurement and wireless data transmission. A comparison of the experimental results and literature data about corrosion shows that the additional corrosion by stray current interference was negligible compared to natural corrosion. Although quantified in a rather crude manner, the additional corrosion for the situation at hand turned out to be lower than 0.2 mm over a period of 100 year.

Keywords: Stray current, DC, railway's, monitoring, field test

1   Introduction

In the Netherlands a total of 6500 km of DC powered railway line exists. Several developments cause the amount of construction work near railway lines to increase. Government policy, for instance, promotes the clustering of (new) railway lines and (new) motorways and condensed building within city limits as opposed to expanding our cities

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beyond their current borders into the rural areas. These developments lead to a large increase of the number of underground (sub)structures in the vicinity of railway lines. Steel and concrete are the main material options for these structures. Compared to concrete, steel provides larger flexibility in the design and construction phase, which results e.g. in reduced construction time. Building in steel is therefore potentially cheaper and causes less nuisance to the surrounding and the train service. Railway owners are, however, wary of accepting steel solutions near railways due to a belief that stray currents can cause significant additional corrosion in steel structures compromising a long and reliable service life.

Stray current is the collective term for all electrical currents running through the ground. Traction power adds significantly to the stray currents. Part of the traction current does not follow the rail as the intended return to the power supply, but leaks into the ground. These currents can interfere with metal parts of buried structures, since these parts can constitute a path with low electrical resistance (stray current interference), back to the original power source. In that case current will enter the steel at one position, flow through the structure, and leave at a different position. There where the current leaves the structure, a risk for corrosion initiation and/or acceleration exists. At present the expertise on stray current corrosion of steel structures is limited and only empirically based. Most experience is gathered in situation when large interference currents occur, e.g. due to faults in the traction power systems. A European standard exists; "Protection against corrosion by stray current from DC systems', EN 50162 [1]. Long term effects are not quantified in this standard. Very limited knowledge exists on magnitudes of stray current interference in case of a properly functioning traction power systems, which can be used to account for this phenomenon in the design phase.

In this paper non destructive monitoring of stray current interference of steel sheet pile structures in a large scale field test is described. The aim was three-fold. Firstly it was the objective to develop and test cost-effective monitoring of stray current interference of sheet pile structures. Secondly it was the objective of this work to get an idea of the order of magnitude of the interference in a relatively worse case scenario. Thirdly the measurements were used to validate a probabilistic design tool, with which stray current durability of underground steel structures can be demonstrated in the design phase. The latter is the topic of a future paper and will not be addressed here.

Interference occurs over the entire surface area of the sheet pile structure with a distributed (non-homogenous) interference current density. Practical interference sensors allow for a local measurement of the interference. To interpret these local measurements in terms of these distributions, the field test was also modelled using the finite element method. Modelling of stray current interference was the topic of several earlier publications, and is therefore only briefly discussed here [2, 3 and 4]. This approach was used earlier by Curcurù et al., who named it imperfect monitoring [5].

Note that the tool and monitoring system were developed for stray current interference in normal conditions as relevant for the design phase. Interference can also occur due to faults e.g. in the construction phase or in the traction power system. Then the interference can be relatively high but occurs for a limited period of time. Such situations are not the aim of the wok described here.

2   Stray current interference and modelling

In Figure 1 a schematic representation of the stray current geometry is depicted. It shows the overhead wire and the rails with in between the train. The Traction Power station (TPS) feeds the traction current into the overhead wires, the current runs through the electromotor of the train and returns to the TPS through the rails. A (small) part of the current leaves the rail and flows into the soil. Before it 'closes the current loop' by re-entering the TPS, it must enter the rails, since the TPS itself is not grounded. Once in the soil the stray current distributes as to minimise the total resistance. If a steel structure is
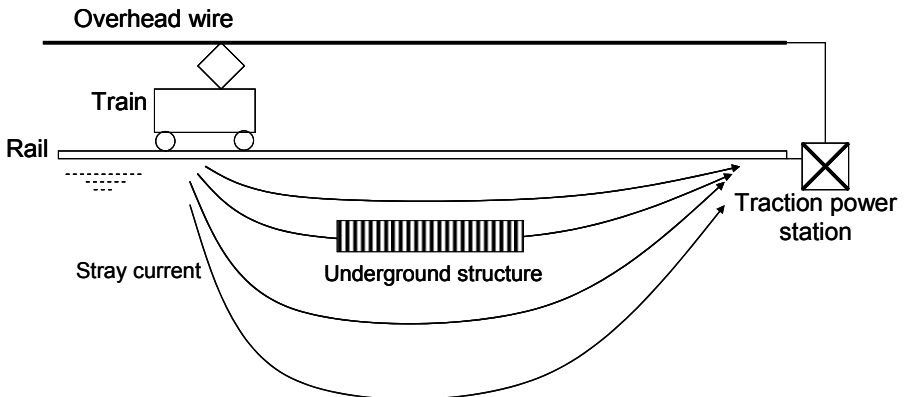

Figure 1. Schematic representation of the stray current geometry

present in the soil, it constitute a return path to the TPS. Current will enter the steel structure, flow through it and will then exit the steel. Since steel is a very good electrical conductor, compared to soil, this current can be relatively high. At the part of the steel surface where the current leaves the structure corrosion can be initiated and accelerated.

In recent papers the finite element model (FEM) of this system was developed using software packages COMSOL and Catpro [2-4]. The details will therefore not be elaborated on here. With the model the electrical current density and associated electrical potential distribution in the traction power system, the soil and the steel structure can be calculated. From the electrical current density leaving the steel sheet piles the (local) corrosion rate and thickness loss can be obtained relatively easily, see Peelen et al. [4]. All necessary and practical input parameters, e.g. from the traction power system can be accounted for in the model. The example model calculation in Figure 2 shows a half sphere which represents the soil. On the position with the red colour the train is present from which current leaks into the soil. On the positions with the blue colour the two modelled TPS's are present, here current enters the rail.
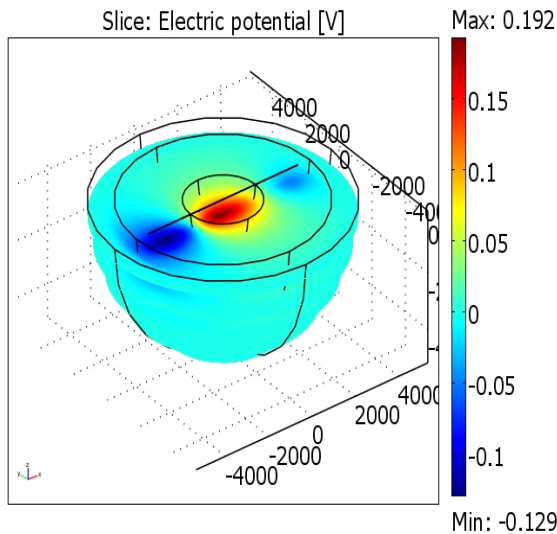

Figure 2. Potential distribution in the soil, obtained in an example calculation with the FEM stray current model (sizes in m, further explained in the text)

3 Field test

The field test has several relevant aspects; the structure itself, its location, the applied sensors and the total of the sensor system, which all will be described below.

3.1 The structure

It was the objective of this work to obtain a direct indication of the amount of stray current interference under practical conditions. Also, the measured results should be readily interpretable in order to be used for a model validation, which is not discussed in this paper. Therefore a not too complex steel structure, but with realistic dimensions, is needed. For stray current interference both the length and the depth of the sheet pile are important to obtain realistic interference current densities. However structure length can be simulated by using two steel sections of much smaller length which are installed at large distance and connected with a thick copper wire with a relatively low electrical resistivity. In many aspects such a structure represents a sheet pile wall with the same length as the distance between the two small sections.

If sheet pile walls are used on a building site, usually there are anchors to keep them in place. These anchors are interesting from a stray current interference point of view. Therefore in the field test an anchor was incorporated.

Therefore two sheet pile walls with a length and depth of 10 meter, separated roughly 220 meter from one another and connected via a cupper cable were implemented. An anchor was buried next to one of the sheet pile walls. The anchor was electrically connected to the two sheet pile walls during the measurements. An impression of the global design is given in Figure 3. The right sheet pile wall is referred to as sheet pile wall A and the left sheet pile wall as sheet pile wall B.

3.2 Location

Possible locations for the field test should fulfil several criteria, both practical and technical. For practical reasons the location should be easily accessibility, the soil should have proper bearing capacity and the available manoeuvring space should be sufficient. Also the soil type should be representative for Dutch soils. Secondly there where some technical criteria; the location should represent a worst case scenario for stray current interference which includes a corrosive soil, small distance from the rail track and a
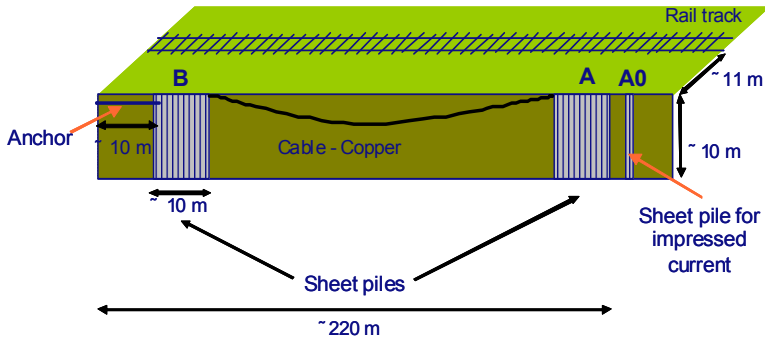
Figure 3. Global design of the field test set-up

location near to a substation. Finally a single railway line with distinct train passages was required in order to obtain signals which could be interpreted in a straightforward manner.

A location was selected next to the railway line between Leiden en Woerden, near Hazerswoude-Rijndijk. All practical requirements mentioned in the previous paragraph were met at this location. The soil type at the location is a combination of peat, clay and sand, which is representative for an aggressive soil in the Netherlands. The nearest substation is at 20 m from the sheet pile wall A, the second one is at approximately 4.6 km in Alphen aan den Rijn, and there is a single (two tracks) railway line. A structure to track distance of 11 and 15 m, for wall A and B, respectively could be realized.

3.3   *Non destructive sensors*

Stray currents will enter and exit the sheet pile wall, and therefore corrosion current densities and steel/soil electrical potentials will change. Therefore two types of sensors are used in this work. One is a specially developed coupon sensor for sheet piles, which gives insight in local stray current densities. The other is a so called reference electrode used to measure the electrical potential differences between the electrode and soil close to the coupon sensors.

The coupon sensor is depicted schematically in Figure 4. A small steel plate with a known surface area of 300x200 mm² made of the same material as the sheet pile wall is attached to the sheet pile in such a way that it is electrically isolated. The plate is electrically connected to the sheet pile wall through a Zero-ohm ampere meter. With this system it is possible to

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measure the current entering or leaving the small steel coupon. From the surface area of the coupon follows the averaged current density. Coupon size and ampere meter sensitivity and accuracy were designed such that very low stray current induced corrosion rates of 1 μm/year could be measured easily. Characteristic for the developed coupon using the zero-ohm ampere meter is that, from the viewpoint of stray current interference it will behave identically as the part of steel on the sheet pile which it covers. Since it is mounted to the sheet pile it is installed together with the sheet pile wall without any further effort. Furthermore it is in exactly the same conditions as the sheet pile wall and its exact location is known. All these facts make this a representative sensor.

A photograph of a sensor is shown in Figure 5. The steel strips on the left and right hand side of the sensor protect it during the drilling process of the sheet pile wall. The coupon is bolted to the sheet pile with four bolts visible on the coupon. They are electrically insulated from the sheet pile with screw tubes of a polymer material (the white parts in Figure 5). Material costs of the sensor are low. Drawback, however, is that applying the sensor to the sheet pile wall is elaborate and involves welding and isolating the coupon from the sheet pile. The two measurement units contain the integrated Zero Ohm Ampere meter and wireless data transport technology, and are buried at a depth of 0.5 m near steel structure A and B. Cabling is guided from the sensors along the sheet piles to the measurements unit, using cable ducts.

Also rather standard sensors were used to measure the electrical steel potential, namely the so-called reference electrodes Copper-Copper Sulfate ($Cu/CuSO_4$) electrodes model Stelth2, type SRE-007-CUY. The electrodes are placed in the ground after the sheet pile
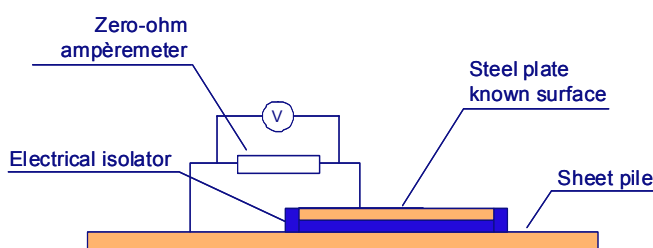

Figure 4. Schematic representation of coupon sensor; insulating material is epoxy, steel plate is same steel as sheet pile

walls were installed. The reference electrodes are lowered into bored holes. After placing the electrodes the holes close automatically around the electrodes due to ground pressure and plasticity of the soil. These electrodes are located at a distance of roughly 300 mm from the sheet pile waals.

Figure 5. Coupon sensor under construction

3.4 *Monitoring system*

On each sheet pile wall 12 coupon sensors and 9 reference electrodes were placed in pairs, except for the lower three coupons. Due to installation difficulties at these depths, here no reference electrodes were placed. The Initial model calculations showed that a roughly homogenous current density distribution over the sheet pile walls would be obtained, but with maxima at the edges. Therefore coupon sensors were placed on the edges of the sheet pile walls and in the middle. The sensors are placed on the side of the sheet pile wall facing the rail track. A schematic impression of the location of the coupon sensors is given in Figure 6. A general rule of thumb in this area is that the ground water level varies between -1.0 and -1.5 meter. Sensors have been placed at about this level in order to observe the impact of the ground water level.

4   Results and discussion

First the sensor behaviour will be discussed, showing that stray current interference information can readily be obtained from the measured data. Next the long term behaviour of the measurements is presented and the distribution of the stray current interference over the sheet pile wall is given and compared with model results. Finally the results are discussed in terms of the consequences for stray current induced corrosion. The monitoring was deployed from May 2009 until March 2010. The longest period of undisturbed measuring was from September 17, 2009 until February 2, 2010. Major problem encountered were flooding of the measurement unit. The measurement frequency could be adjusted and varied between every 10 s to every 40 s.

4.1   Sensor behaviour

In Figure 7 the measured steel potential of the anchor tip is depicted during one day. In the night period in which there are no trains passing, clearly a different pattern is seen, compared to the other part of the day. The peaks visible in the graph indicate the passing
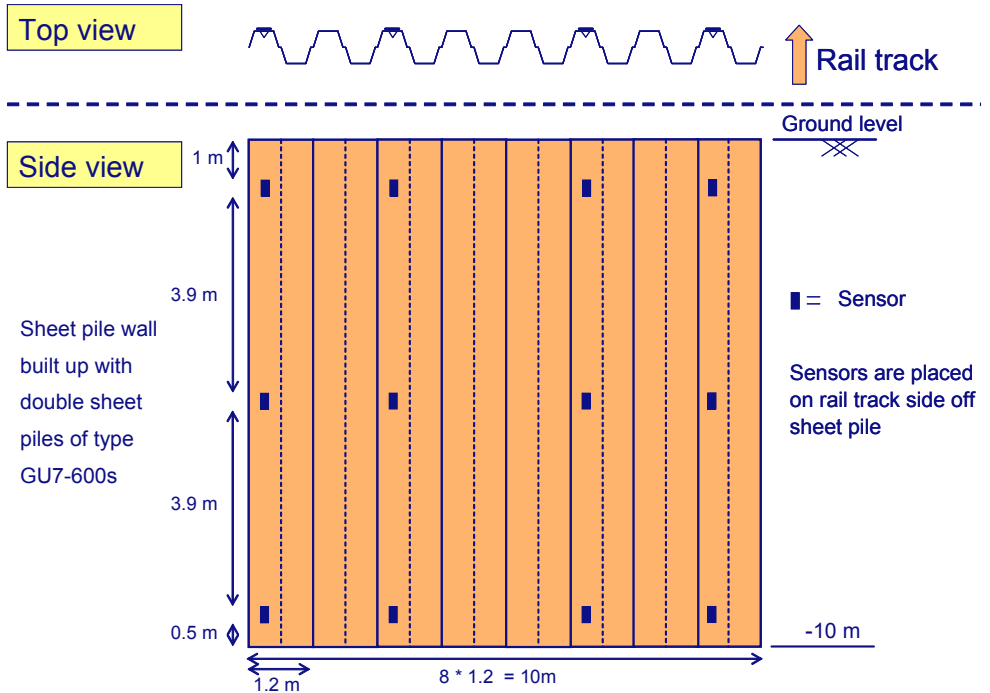

Figure 6. Schematic representation of the coupon sensor system on the sheet pile wall

of trains and stray current interference. A period of 30 minutes between the peaks could be discriminated. Comparison with the train schedule indeed showed a passing train interval of 30 minutes. The same pattern was observed for most of the other sensors.

A single coupon measurement at a depth of 1 m over a one day period is shown in Figure 8. The red line represents the raw measurement data. The black line shows the signal after post processing. This post processing involves the removing of low frequency components (means, long period trends) and high frequency contents (noise). Further post processing was performed, in which use is made of Fourier Transforms in order to identify dominant frequencies (or periods) in the signal. Doing so, a period of 30 minutes is to be expected, from the train schedule. Figure 9 presents the result of such a transform for the signal in Figure 8. The top graph presents the Fourier transform to the frequency domain of the measurements. The lower graph shows the results after the back transform to the time domain. Note that the lower graph represents the signals measured during one full day. Indeed a clear period is obtained of 30 minutes.

Train passages are shown to give rise to stray current magnitudes in the order of 10 µA for this coupon location. The coupon sensor also shows the same characteristic difference between day and night as the potential measurement. Note that train passages are visible
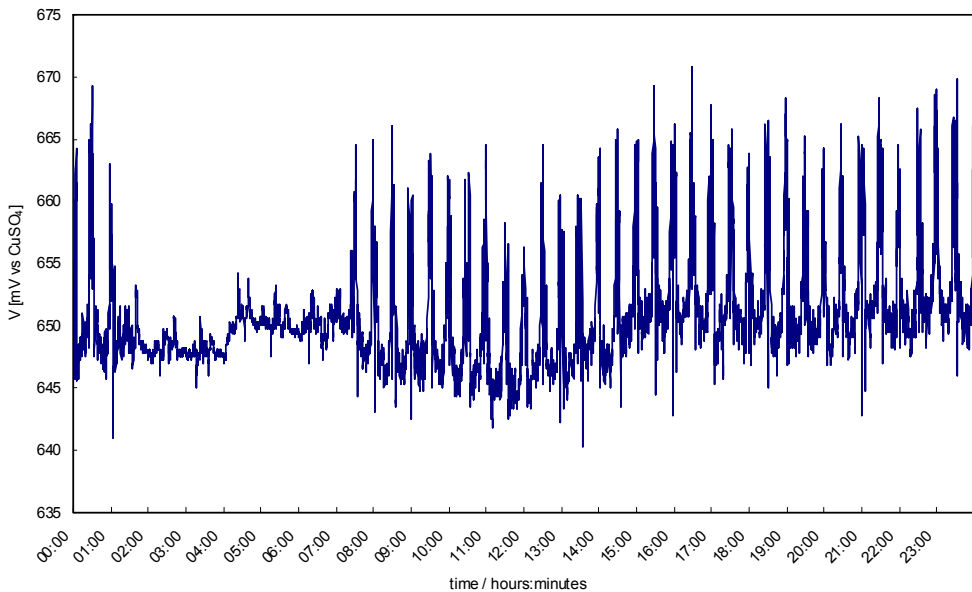

Figure 7. Weekend day potential measurements at anchor

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in the measured current for a period of roughly 3 minutes, corresponding with an interference distance of 6 km, which stems from the interference of the train from different positions while it is moving towards and from the field test position. These graphs offer several options for interpretation. From integrating the currents under the peak the charge transferred during passage of a train is obtained. This charge can be calculated to a thickness loss of the sheet piles, due to stray current corrosion [4]. An easier, but cruder interpretation, giving a more conservative result, is to take the peak height as measure for the average corrosion rate over the entire period of the train passing.

In the current and potential data offset values are observed, not stemming from stray current interference. The magnitudes of these currents are between several to several hundred micro amps. Several phenomena can be responsible for these offset currents, which cannot be discriminated here. The origin of these currents was therefore not investigated as part of this part. However, when interpreting these currents as corrosion currents, all these values are relatively small compared to corrosion rates mentioned in standards for sheet pile walls, which are in the order of several mm in 100 years. Use of these values must however be done with extreme caution and by corrosion experts with
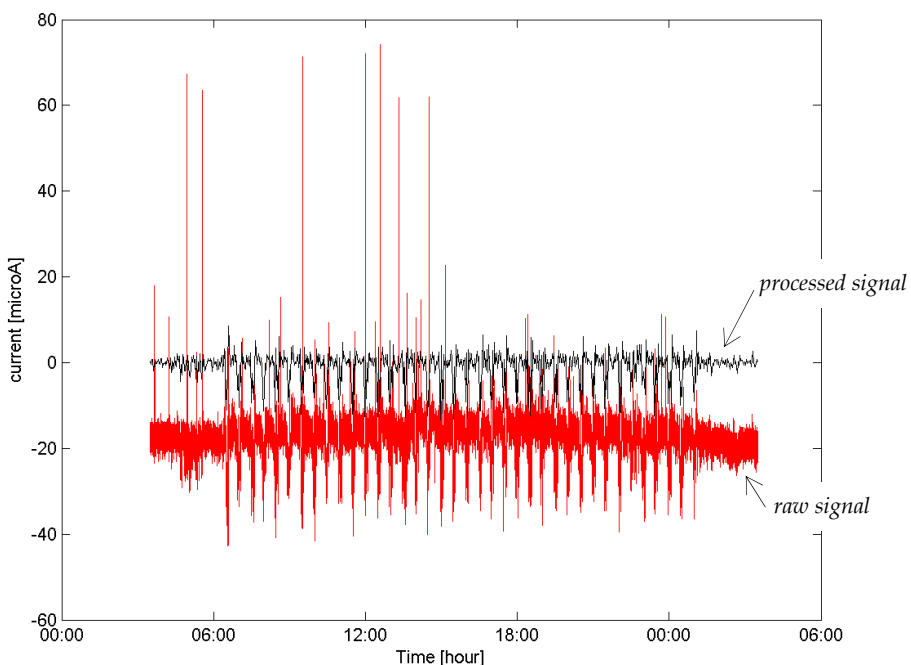

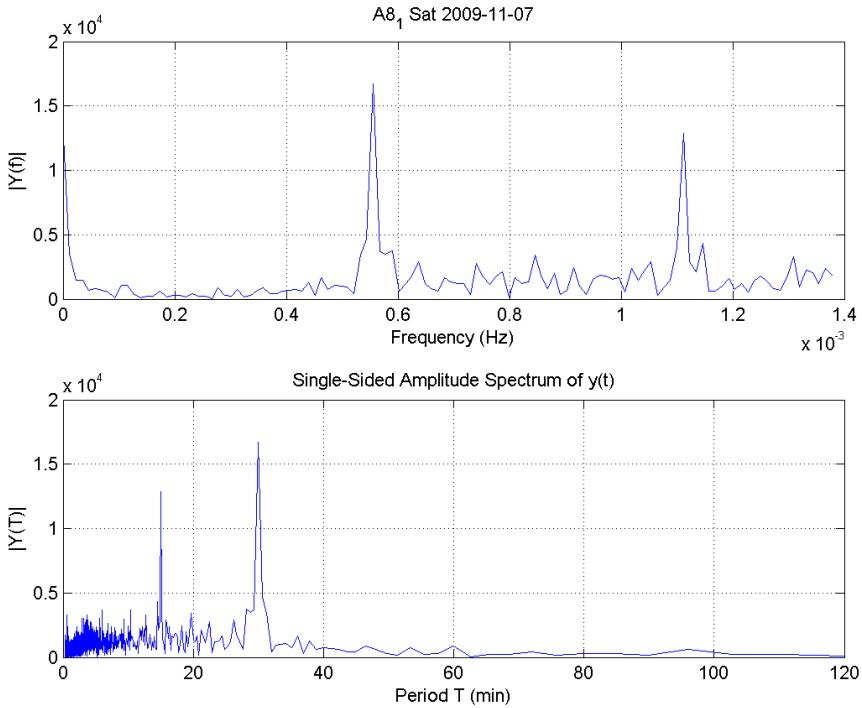*Figure 8. Coupon signals of Saturday Nov. 7, 2009*

Figure 9. Frequency spectrum of coupon measurement shown in Figure 8 (top) and corresponding dominant periods (bottom)

detailed knowledge of the field test. Note that the coupon sensors were developed for measuring stray currents interference and were not designed for the phenomena causing the offsets.

4.2 *Distribution*

From the processed signals the maximum amplitudes for the different coupon locations can be plotted in a schematic way as in Figure 10. Thus, the geometrical distribution of the measured stray current values can be visualised. In general, the values found in the sheet piles are (very) low. Relatively high values are found at and near the anchor, with increasing values towards a maximum at the anchor end points. The value indicated with green is relatively unstable in time, most probably the sensor is not functioning properly. Over time, these plots show a fairly constant behaviour of the values. This measured geometrical distribution is compared with the calculated geometrical distribution, as shown in Figure 11. The model tends to over estimate the magnitude of the interference. However, in general the measured distribution is reproduced by the model. This indicates
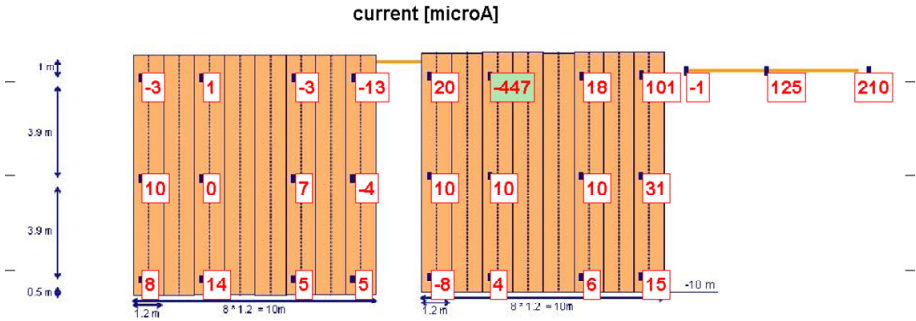
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current [microA]

Figure 10. Maximum values per coupon location and anchor (on the right hand side), Saturday Nov. 7, 2009
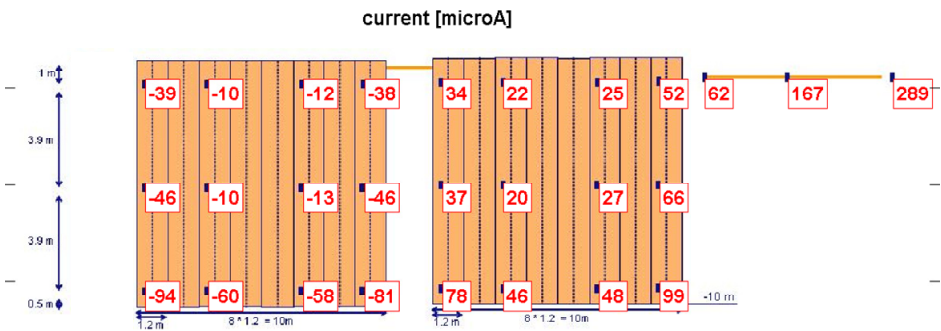
current [microA]

Figure 11. Modelled maximum values per coupon

that the distribution delivered by the monitoring system developed in this work is representative for stray current interference.

4.3 *Long term behaviour*

So far only measurements obtained over a small time scale are shown. The measured maximum values tended to fluctuate during time in a rather erratic way. This is probably due to the fact that the measured values are relatively small. Long term behaviour was therefore studied by obtaining the distribution of the measured maximum values. Such a graph is presented Figure 12 for the coupon at the anchor tip. In this cumulative distribution function the empirical (measured) probability of measuring a peak current lower than a certain value is given. This distribution indicates that the probability of measuring a peak value lower than 50 µA is roughly zero. Then a steady increase in the probability of measuring peak values between 75 and 175 µA from roughly 10 to 90% is

obtained. About 10% of the measured peak values are between 175 and 250 µA. Finally the probability to measure peak values of 250 µA or higher is zero.

For the other coupon similar but less distinct distributions were obtained, due to the low measured current densities. Aim of this paper was also to get an idea of the order of magnitude of stray current induced corrosion of sheet pile structures. Since the measured current densities are low, the additional corrosion due to stray currents stemming from train passages, are low too. These are quantified further below.

The cumulative distribution obtained at the anchor tip, which shows largest stray current densities of all location, is used for the long term interpretation of measured results. The peak value of 196 µA at 95% percentile is taken as the interference measured continuously during the passage of a train (3 minutes) and using the current train schedule, over 100 years. In this way a (very) conservative assessment of the stray current interference is obtained. From this value a thickness loss can be calculated of 0.2 mm in 100 years, due to train passage induced stray currents [1]. Note that this additional corrosion was obtained
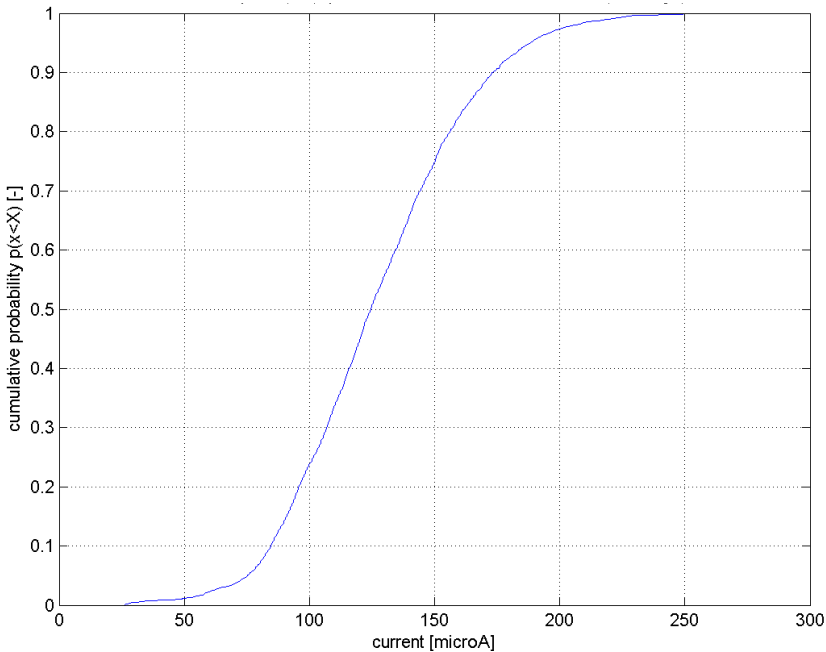

Figure 12. Cumulative distribution function of the current density at the anchor endpoint, in period Oct. 4, 2009 until Feb. 2, 2010 (101 days)

under the specific experimental conditions used in this work, and cannot be generalized. The 95% percentile in natural corrosion can be determined at 3.1 mm and 2.3 mm in peat and clay respectively, using distributions for natural corrosion in 100 years [1, 4]. Therefore additional corrosion of 0.2 mm in 100 years, in a worse case scenario, is far smaller than the natural corrosion rates.

5   Conclusions

Additional corrosion due to DC traction stray currents was successfully identified and detected using two types of sensors and a steel structure representing a length of 200 meter near a power station containing an anchor directed towards such a station. The determination of the location of the sensors using finite element modelling successfully eliminated doubts over imperfect monitoring. The specially developed coupon sensors worked properly. Material costs of the sensors were low, but installation time was high.

Very low stray current induced current densities on the sheet piles were obtained, although the conditions; type of soil, sheet pile wall length, sheet pile depth and the position of the structure was optimised to obtain high current densities. Under these circumstances, the additional corrosion by stray currents was determined to be less than 10% of the natural corrosion in a rather crude and conservative way.

This shows that from a design point of view stray current interference would be low under the circumstances of the field test. Since these circumstances are considered representative for normal well controlled situations, we may conclude that stray current corrosion is limited and can be addressed with appropriate measures in the design phase, also for structures with different geometries as addressed here. These measures should be developed by stray current corrosion specialists. Note that also risks from malfunctioning traction power systems which are known to be able to cause major stray current corrosion should be addressed.

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